

**CARBON BLACK FROM WASTE TIRES: A SYSTEM DYNAMICS PERSPECTIVE****Alyson da Luz Pereira Rodrigues, \*Erik Eduardo Rego, Thalissa de Oliveira Elias Reis,  
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**Abstract**

This study advances the understanding of pyrolytic carbon black (CBp) production from waste tires by addressing a critical research gap: the absence of integrated, system-level modeling for industrial-scale pyrolysis operations. While pilot-scale studies have demonstrated the technical promise of thermal pyrolysis, existing literature rarely considers the complex, multidimensional interactions that shape large-scale feasibility. The novelty of this work lies in its application of a participatory systems thinking approach - operationalized through group model building with interdisciplinary stakeholders - to develop a holistic model of waste tire pyrolysis. The approach systematically integrates five interdependent dimensions: market, environmental, economic, technical, and political. This process enables the collaborative identification of causal structures, feedback loops, and systemic constraints, producing a robust framework for simulating future scenarios and policy interventions. The models serve as dynamic decision-support tools for strategic planning, capturing the interplay between key variables and enabling the assessment of multidimensional impacts. By linking system-level understanding with practical strategy formulation, this research provides a pathway for the design and deployment of efficient, sustainable pyrolysis facilities - positioning CBp recovery as a viable component of a circular economy for waste tire management.

**Keywords:** Carbon black market, Waste valorization, System dynamics, Group model building, LCCB.

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**INTRODUCTION**

The continuous and accelerated development of the automotive industry has a direct impact on tire utilization and production (Wu *et al.*, 2021; Zerim *et al.*, 2023; Yusha *et al.*, 2024). Estimates indicate that approximately 26 million tons of used tires are generated annually worldwide, projected to increase by 70% over the next 30 years (Magagula *et al.*, 2023; Rosner *et al.*, 2024). By the end of the 2030, the annual weight of discarded tires is expected to reach 1.2 billion tons (Xu *et al.*, 2021; Guo *et al.*, 2024). The disposal of waste tires poses numerous environmental risks, including the leakage of toxic substances into water and soil, fire hazards, among others (Xu *et al.*, 2021; Moasas *et al.*, 2022; Zerim *et al.*, 2023). Thus, the international community recognizes the importance of recycling and reusing waste tires as a vital practice for environmental conservation and energy efficiency. Despite pyrolysis being a well-known process, initially used to synthesize charcoal, the first applications for waste tires date back to the 1970s, with the oil crisis (Zabaniotou *et al.*, 2014; Martinez *et al.*, 2021). As a result, there is a growing amount of literature that recognizes the importance of applying pyrolysis technology to reduce the number of waste tires to pyrolytic carbon black (CBp) (Martinez *et al.*, 2013; Xu *et al.*, 2018; Xu *et al.*, 2021; Moasas *et al.*, 2022; Zerim *et al.*, 2023; Magagula *et al.*, 2023). CBp also known as pyrolytic char is a fine carbon particle, composed of graphite-like carbon layer stacks (Zerim *et al.*, 2023) and classified as a large-scale commodity with a market size of 19.3 billion USD in 2023 (Rosner *et al.*, 2024; Precedence Research, 2023). Researchers claim that the thermal pyrolysis technology is considered as one of the ideal methods of reducing and recycling waste tire (Xu *et al.*, 2018; Xu *et al.*, 2020; Xu *et al.*, 2021; Wu *et al.*, 2021; Zerim *et al.*, 2023; Yusha *et al.*, 2024).

Therefore, most academic literature on CBp focuses on a variety of pyrolysis technologies, including co-pyrolysis (Hossain *et al.*, 2017; Wang *et al.*, 2018; Zhang *et al.*, 2022), catalytic pyrolysis (Zandi *et al.*, 2018), and vacuum pyrolysis (Karagoz *et al.*, 2020; Zhang *et al.*, 2008), as alternative processes for the production pathways of carbon black. Regarding modeling, Wu *et al.*, (2021) conducted a comparison of the life cycle assessment (LCA) of the pyrolysis of waste tires. Bi *et al.*, (2022) studied the simulation and technical-economic analysis of the pyrolysis process of waste tires based on the kinetics of the process. Rosner *et al.*, (2024) modeled the CBp production process to provide insights into mass and energy balances, economics and environmental analysis. Yusha *et al.*, (2024) reviewed current advances in waste tire valorization with a focus on process simulation and system optimization. However, there has been limited emphasis on the systemic modeling of the practical aspects of waste tire pyrolysis on an industrial scale. Although previous attempts have contributed to mitigate the environmental issue caused by waste tires (Martinez *et al.*, 2013; Wu *et al.*, 2021; Xu *et al.*, 2021; Zerim *et al.*, 2023; Guo *et al.*, 2024), the integration of several aspects related to the feasibility of the industrial production of carbon black have still to be investigated. Nevertheless, the industrial-scale pyrolysis of waste tires presents a formidable interdisciplinary challenge, encompassing market, environmental, technical, economic and political constraints. Thus, the interplay of numerous factors introduces a high degree of uncertainty, classifying it as a complex adaptive system (CAS) (Sterman, 2000; George *et al.*, 2015; Bala *et al.*, 2017; Matham *et al.*, 2023). However, there is a lack of research on developing risk analysis frameworks for assessing the feasibility of industrial-scale waste tire pyrolysis. To overcome this challenge, studies are needed that use systemic approaches, considering dynamically the multiple and complex interdependencies between the market, environmental, economic, technical and political dimensions

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for holistic decision-making, as a process that integrates various aspects, perspectives and information before reaching a conclusion or choice, considering the long-term impacts and interconnections between different variables (Monge *et al.*, 2021; Almollahi *et al.*, 2024). This research aims to address the gaps mentioned above by developing a new framework based on Systems Thinking (ST) to understand and describe system behaviors comprehensively, offering a holistic analysis of associated problem. The choice this approach is justified for several reasons. Firstly, it is well-suited for analyzing complex macro-systems such as industry, environment, and economy, due to its ability to capture causal relationships among different key variables within these systems (Williams *et al.*, 2017; Pagano *et al.*, 2019; Purwanto *et al.*, 2019; Esfandabadi *et al.*, 2020; Monge *et al.*, 2021). Secondly, this approach integrates the multidimensionality of various disciplines through participatory modeling among researchers, supporting stakeholders in making critical strategic decisions within the industrial sector (Andersen *et al.*, 2007; Gebrai *et al.*, 2021; Matham *et al.*, 2023; Kotir *et al.*, 2024; Pluchinota *et al.*, 2024). Ultimately, our framework not only assists future modelers, investors, researchers, engineers, and policymakers but also provides a foundational basis for employing other modeling approaches. This article begins with a description of the global carbon black market, essential for developing its modeling. The system dynamics methodology used is then presented.

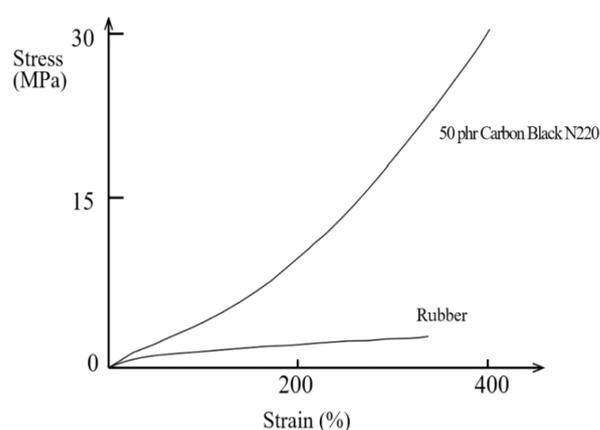
### Carbon Black Market overview

Carbon black is a finely divided carbon powder produced through the partial combustion of heavy hydrocarbons, such as residual oils or coal tar. These raw materials are typically by-products of the oil refining process, obtained after separating other lighter fractions, such as decanted oil from FCC (Fluid Catalytic Cracking). These feedstocks are generally unsuitable for direct combustion and conversion into fuel because they contain sulfur and other heavy metals in their composition. Furthermore, they have low calorific value, partly due to their high viscosity, which hinders the atomization required for efficient combustion and fuel conversion. On the other hand, their long aromatic chains allow the production of aggregates with a high carbon content, an essential characteristic for different types of carbon black, which typically have a purity level above 90%.

Its physical and chemical properties – such as thermal and chemical stability, light and UV radiation absorption capacity, and influence on composite viscosity – enable its application in various industries. In 2024, the carbon black market was valued at USD 19.3 billion, showing a compound annual growth rate (CAGR) of about 3.6% between 2018 and 2024 (Technavio, 2024). Although it is a versatile material with multiple industrial applications, most of its revenue comes from rubber applications, especially as a reinforcing agent in tires – a segment that accounted for about 71% of the market in 2024. Regarding the geographical distribution of the carbon black market, the Asia-Pacific region is in the lead, accounting for about 43% of the sector's revenue in 2024. Notable countries in this region include China, India, and Malaysia, which, in addition to being significant consumers, are also major producers – especially China, the world's largest exporter of carbon black. North America is the third-largest consumer market (16.2%), behind Europe (18.3%).

### Properties and Production Process

Carbon black is applied to a wide variety of materials to improve their physical, electrical, and optical properties. As noted above, its largest use by volume is as a reinforcing and performance-enhancing additive in rubber products. In rubber compound formulation, natural and synthetic elastomers are mixed with carbon black, elemental sulfur, processing oils, and organic chemicals, and are then heated to produce a wide range of vulcanized rubber products. In these applications, carbon black provides reinforcement and improves resilience, tear resistance, conductivity, and other physical properties. Carbon black increases the hardness and viscosity of rubber-based compounds and is considered the most efficient additive among all filler materials. Figure 1 shows a performance comparison of a rubber compound with and without carbon black as a reinforcing agent. From the stress-strain graph, it can be seen that pure rubber compound exhibits low mechanical strength, evidenced by a considerable increase in deformation even for a small increase in stress. This curve characterizes a highly elastic but not very strong material, which is desirable for rubber but lacks resistance. With the addition of 50 phr (parts per hundred rubber) of N220-type carbon black, there is a significant increase in the stress the material can withstand as deformation intensifies, thus proving carbon black's role as a powerful reinforcing agent, capable of increasing rigidity, tensile strength, and the ability to absorb mechanical energy in rubber compounds. Several characteristics of carbon black influence the degree of reinforcement performance. Microstructure, specific surface area, and aggregate morphology are considered key properties that affect the interaction between carbon black and elastomers. The specific surface area ( $\text{m}^2/\text{g}$ ) of carbon black is a function of particle size: geometrically, smaller primary particles have a larger specific surface area. Microstructure refers to the three-dimensional arrangement of the primary particles in the carbon black aggregate. Extensive interlinking or branching characterizes a "high structure," whereas less pronounced interlinking indicates a "low structure."



Source: FAN; FOWLER; ZHAO (2020)

**Figure 1. Stress-Strain Curve for a Rubber Compound with and without Carbon Black**

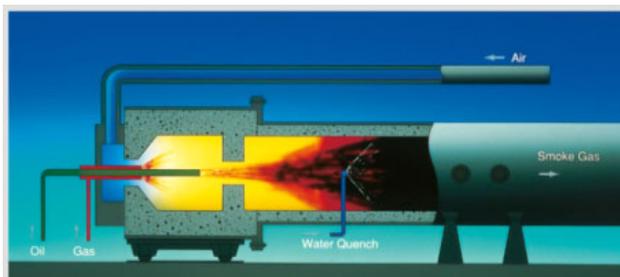
The diameter of carbon black particles usually ranges from 10 nm to 500 nm. While larger diameter particles tend to present a more graphitic structure, as particle size decreases, dispersion of carbon black in rubber compounds improves, increasing the surface area – that is, the contact area between the carbon black and the elastomer – and thus yielding better reinforcement performance. Carbon blacks classified above

N330 (with particle diameters greater than 300 nm) are considered “semi-reinforcing,” while those with diameters below 35 nm are classified as “super abrasion” grades. This diversity of types, formed from different combinations of particle sizes and structure/aggregation, allows carbon black to be used in various industries. In addition to rubber reinforcement, carbon black is used as a black pigment and as an additive to improve the performance of other materials, including conductivity, viscosity, electrostatic charge control, and UV protection. This type of carbon black (typically called specialty carbon black) is employed in a variety of applications in the coatings, polymers, and printing industries, as well as in other specialty uses (Orion, 2022).

## Production Process

The basic raw material for producing carbon black consists of aromatic hydrocarbons that are decomposed into their constituent elements – carbon and hydrogen – through a thermal or thermo-oxidative process (partial combustion). From an economic standpoint, thermo-oxidative decomposition has become the predominant method; in this process, hydrocarbons play a dual role, acting both as a heat source for combustion and as a carbon source for the carbon black composition. Every production method is based on two fundamental elements: heat and decomposition. The way these steps are organized defines the differences between production processes.

The most recently developed process, the furnace black method, has become the most common for large-scale carbon black manufacturing, accounting for 98% of annual production. This continuous method uses liquid hydrocarbons as feedstock and gaseous hydrocarbons as a heat source. When natural gas is available, the liquid feedstock is atomized into a heat source generated by the combustion of natural gas with preheated air. As the reaction occurs at very high temperatures, it is confined to a refractory-lined chamber, whose name (furnace) explains the origin of the process name (see Figure 2). Thermal decomposition (pyrolysis) of the feedstock and carbon black growth occur in this reaction zone. The exhaust gas (flue gas) formed during the conversion of feedstock into carbon black contains carbon monoxide, hydrogen, and steam, which, at the reaction zone temperature, react with the carbon black. These secondary reactions reduce process yield, so to avoid such losses, the process gas mixture is rapidly cooled by water injection.



Source: Orion, 2022

**Figure 2. Furnace Black Reactor Diagram**

The carbon black-laden exhaust gas then passes through a heat exchanger for additional cooling. Once temperatures drop below 400 °C, the carbon black is separated from the residual gas using bag filters. Approximately 50–60% of the feedstock is converted into carbon black. The gases produced in the

reaction are combustible and, in most cases, are sent to an afterburner, where the heat generated is used to dry the carbon black, or burned in a boiler to produce steam. The carbon black discharged from the filters is pneumatically conveyed to other processing sections. Magnetic and mechanical separators are used to purify the material from contaminants such as coke particles (“grit”), abrasive particles from the furnace’s refractory lining, or rust particles. The furnace process produces a lightweight powder with low bulk density, which is difficult to handle and transport. One essential step is converting this material into a higher bulk density powder while maintaining free flow. This is usually done via a wet pelletizing process with water, which must be controlled so that the pellets are strong enough for transport and handling but weak enough to easily break down in the final application. The pellets are then dried and packaged.

The furnace black method offers environmental and occupational safety advantages. The fully enclosed installation keeps process gas and dust emissions to a minimum. In addition to its environmental, economic, and technical benefits, this method also provides greater flexibility, as it can produce a wider variety of carbon black types than any other process currently in use. All raw materials are strictly specified in terms of quality, type, and quantity, allowing a wide range of carbon blacks suitable for various applications to be produced without fundamental changes to the process for each product variant. Particle size or specific surface area can be set from the start by properly configuring process parameters, enabling the production of carbon black with primary particle sizes ranging from 10 to 80 nm. High reaction temperatures, low feedstock injection rates, and rapid quenching, for example, favor the formation of small particles (with high surface area). This method also allows control over particle aggregation (i.e., carbon black structure) by adding small amounts of alkali metal salts. On the other hand, the carbon footprint associated with carbon black production is significant – it is estimated that producing one ton of carbon black emits approximately 2.4 tons of carbon dioxide.

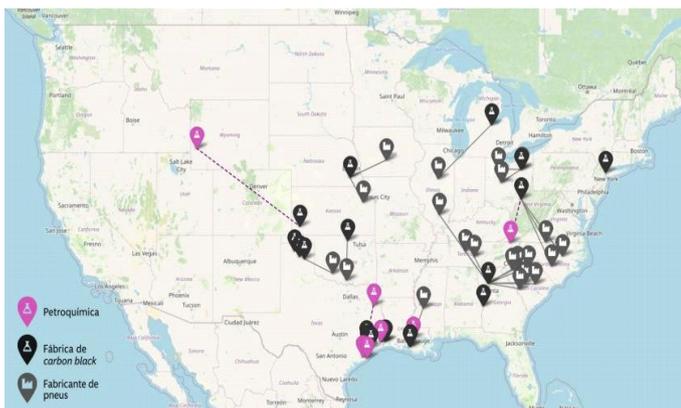
## Cost Structure of the Production Process

In addition to a considerable carbon footprint, the production process also has a relevant cost structure, an essential aspect when analyzing base industrial product companies. Based on a computer simulation of furnace black production, Rosner et al. (2023) estimated the contribution of various process items to the levelized cost of carbon black. The results show a structure where most costs are variable, with raw material purchases accounting for about 66% of production costs, followed by overnight Capital Cost with 12%, labor cost with 9%, Natural Gas and Electricity with 5%.

## Factory Location

As carbon black is a high bulk density, low value-per-kilogram input, it is economically more sensitive to logistics costs, with transport expenses representing a significant portion of the final product cost. In addition, it has an intensive supply chain, involving both the transportation of raw materials (such as heavy aromatic oils or natural gas) to the production plants and the distribution of the finished product to consuming industries. To deepen the understanding of the production structure and the logistics involved, the plants of the main carbon black producers, major tire manufacturers, and

petrochemical suppliers (which provide feedstocks for carbon black companies) were mapped. Data collection was carried out through research in secondary sources, such as corporate reports and company websites, and plant locations were converted into geographic coordinates. Using the Folium library in Python, maps were developed showing the locations, and logistical connections were simulated based on the shortest geodesic distance between points. This allows a better understanding of the carbon black logistics dynamics for each region, starting with the United States, shown in Figure 3.



**Figure 3. Carbon Black Supply Chain Locations in the United States**

In this region, for carbon black production, plants from Cabot Corporation, Orion Engineered Carbons, Birla Carbon, Continental Carbon, and Monolith were considered. For the tire sector, production units of groups with significant presence in the North American market were mapped, including Goodyear, Michelin, Bridgestone, and Continental. Petrochemical sources were represented by plants from ExxonMobil, Chevron Phillips, Eastman Chemical, and Dow Chemical, prioritizing refineries and facilities producing aromatic feedstocks used in carbon black manufacturing. In the United States, there is a concentration of tire manufacturers in the southern and southeastern regions, in states such as North Carolina and South Carolina, while petrochemicals are concentrated in Texas, mainly in the Gulf of Mexico region. Carbon black plants are positioned both to meet demand, with some located in Georgia close to tire manufacturers, and to be near feedstock suppliers, with other plants located in Texas. Despite the presence of these industrial clusters, the average distance between petrochemicals and the nearest carbon black plant is 668 km. The average distance to tire factories is shorter, around 300 km. This closer proximity to consumer markets is consistent given that transporting the finished product presents significantly more complex logistical and operational challenges than transporting raw materials. Although aromatic oils are flammable liquids, their transport, mainly via tanker trucks, is technically well established and relatively lower-risk. Conversely, carbon black, in its fine powder or granular form, is highly adhesive and dispersive, and is also classified as a combustible dust. Therefore, its transport requires strict dust containment, filtration systems, and specific packaging (such as big bags or sealed sacks), increasing operational costs per ton. In Europe, transport is facilitated by an extensive rail network as well as free movement and trade agreements between EU countries. Thus, although there is a clear industrial cluster in the northern France region, encompassing northern Germany, Belgium, and the Netherlands, tire factories are scattered throughout the

continent. Carbon black plants, in turn, are concentrated in the same industrial cluster but also have some dispersed units, such as in northern Spain, Italy, and parts of Eastern Europe. This dispersion allows companies to be close to their consumer markets, with an average distance of 177 km between tire plants and the nearest carbon black plant. In contrast to the United States, they are also close to their suppliers, with an average distance of about 100 km between petrochemicals and carbon black plants. This more compact supply chain is favored by Europe's geographical characteristics, with smaller and more industrialized countries. Figure 4 illustrates these supply chain characteristics in Europe. For this, carbon black plants belonging to Cabot Corporation, Orion Engineered Carbons, Birla Carbon, Tokai Carbon, Continental Carbon, and PCBL were considered, along with tire factories from Michelin, Bridgestone, Continental, Pirelli, and Goodyear, and petrochemicals from BASF, Shell, ExxonMobil, Total Energies, INEOS, and Repsol.



**Figure 4. Carbon Black Supply Chain Locations in Europe**

In Asia, the supply chain is concentrated in a few countries, such as China, Japan, and India. While the Asia-Pacific region accounted for 43% of the carbon black market in 2024, these three countries together represented about 38%, showing their relevance both regionally and globally. This concentration of both tire industries and carbon black plants results in an average distance of about 628 km, relatively low given the size of the Asian continent. The distance between carbon black plants and their suppliers is similar, around 594 km. Factors such as rapid growth in vehicle demand in Asia, lower operating costs, and more flexible industrial policies explain the region's position as the growth epicenter of the carbon black supply chain. The location of the main companies involved is shown in Figure 5. In carbon black production, plants from Cabot Corporation, Birla Carbon, Orion Engineered Carbons, Tokai Carbon, and PCBL were included. For tire manufacturers, Michelin, Bridgestone, Goodyear, Sumitomo, Hankook, Kumho, Nexen, Apollo, MRF, CEAT, JK Tyre, Continental, Giti, ZC Rubber, Triangle, Sailun, and Double Coin were included. Petrochemical units considered belonged to Sinopec, CNPC, Dow Chemical, Petronas, Eastman Chemical, and Aramco Asia. It is worth noting that, as China has a strong presence of local carbon black producers such as Blackcat, the analysis is limited by low data disclosure from these Chinese companies.

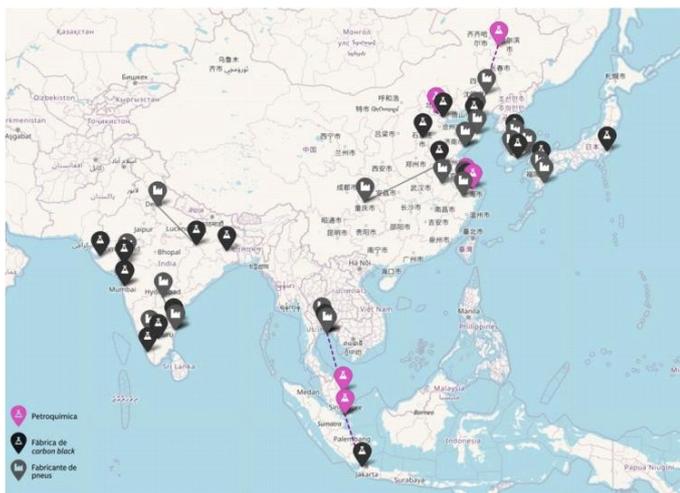


Figure 5. Carbon Black Supply Chain Locations in Asia

### Global Supply, Trade Dynamics, and Demand Analysis for Carbon Black

In addition to concentrating demand for carbon black, Asia also accounts for a significant share of global production capacity approximately 70%. Although the region, particularly China, has held this leading position for years, with 48% of share (Notch Consulting), recent trends indicate a subtle shift in global production capacity toward the Asian continent. While China is also a major consumer of carbon black, its production capacity comfortably exceeds domestic demand, resulting in consistent surpluses over the years. These conditions position China as the world's largest exporter, accounting for 17.4% of global export value and 22.2% of global export volume.

China's production is heavily concentrated in basic grades of carbon black, with comparatively lower output of specialty grades. Consequently, the country tends to export lower value-added grades (with lower unit prices) while importing higher-value types. This is evidenced by the gap between the average export price (US\$1,250/ton) and the average import price (US\$1,920/ton) (Notch Consulting). On the other hand, Japan and several European countries, notably Belgium and Germany export higher unit value carbon blacks for specialty applications while importing lower-cost grades to meet domestic demand.

#### Demand Analysis

A key characteristic of carbon black is that it is an intermediate good used as a raw material in the manufacture of other products. Consequently, carbon black producers operate exclusively in a business-to-business (B2B) model, with their customers being entirely other companies. These customers are primarily industrial goods manufacturers, most notably within the automotive sector, which accounts for 70% of demand. Within this sector, the dominant application is in tires, both for the original equipment market and for replacements. As a result, carbon black producers' revenues are often heavily concentrated among these large tire manufacturers. Sales to such clients are typically governed by long-term supply contracts, in which prices are indexed to raw material costs with quarterly or annual adjustments. These contracts often include minimum purchase commitments and dedicated production capacity to ensure supply to these key customers.

While tires remain the dominant application, carbon black is also used in other automotive parts, such as belts, coating paints, and increasingly in electric vehicle (EV) batteries.

Demand for carbon black is therefore closely tied to the performance and cyclical patterns of the automotive industry. In emerging economies, new vehicle demand is driven primarily by growth in per capita income and the expansion of the middle class. In countries such as India, Indonesia, Mexico, and Brazil - where vehicle purchases are predominantly financed - credit availability is also a critical determinant. Rapid urbanization in developing regions also creates significant mobility pressures. Combined with limited public transport infrastructure, these factors encourage private vehicle use as a practical and accessible mobility solution. This is particularly relevant for countries with relatively low motorization rates compared to their population size. According to the International Organization of Motor Vehicle Manufacturers (OICA), in 2020 the average number of vehicles per 1,000 inhabitants was 518 in Europe, but only 143 in Asia and 49 in Africa. Between 2015 and 2020, Asia's vehicle fleet grew at an average annual rate of 8%, four times the European growth rate. China, India, and Vietnam stood out with average annual growth rates of 14%, 10%, and 17%, respectively.

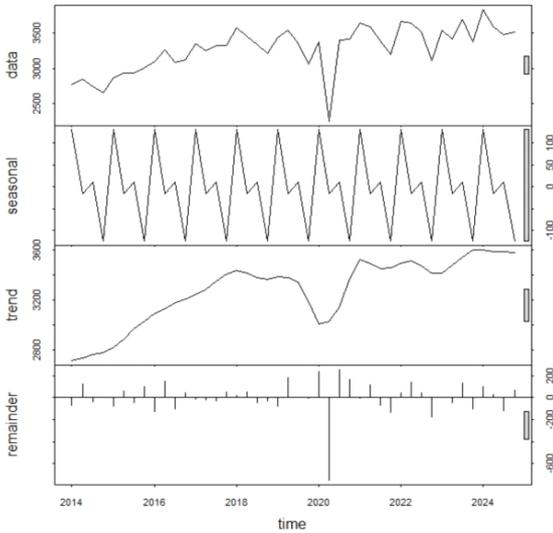
In emerging economies, tire demand is generally driven by the cyclical growth in new vehicle sales. In developed countries, however, demand is predominantly for replacement tires, which account for over 60% of total tire consumption. As such, tire (and therefore carbon black) demand includes a countercyclical element: replacement tire consumption is driven by the size of the vehicle fleet, its average age, and total mileage. Higher mileage directly increases tire wear, leading to greater replacement needs. An older fleet, having accumulated more mileage, tends to require more frequent preventive maintenance - tire replacement being one of the most common interventions. Beyond the automotive sector, growth in construction, infrastructure, electronics, and consumer goods industries also supports carbon black demand. In all these sectors, demand for carbon black is closely linked to broader industrial activity.

A notable emerging application is in electric vehicles. In addition to its role as a reinforcing agent in tires, carbon black is used as a conductive additive in lithium-ion battery electrodes, improving electron transport and overall battery performance. Conductive plastics—used in electronic modules, housings, connectors, and electromagnetic shielding—also incorporate carbon black to ensure static dissipation and thermal resistance.

#### Quantitative Demand Study

To provide a more robust, data-driven understanding of demand behavior, an econometric model was developed using quarterly data from 2014 to 2024, totaling 44 observations for each variable analyzed. The dependent variable in the model is the global volume of carbon black demanded (in thousand tons). Using the statistical software **R**, a preliminary graphical analysis was conducted on the demand time series, as shown in Figure 6. The decomposition reveals three main components: trend, seasonality, and noise. The trend shows a general upward trajectory over the period, with stronger growth prior to 2020. The seasonal component indicates recurring annual

patterns, with demand typically peaking in the first quarter of each year. The noise component captures random fluctuations not explained by trend or seasonality, with the most pronounced disturbance occurring in 2020, reflecting the shock from the Covid-19 pandemic.



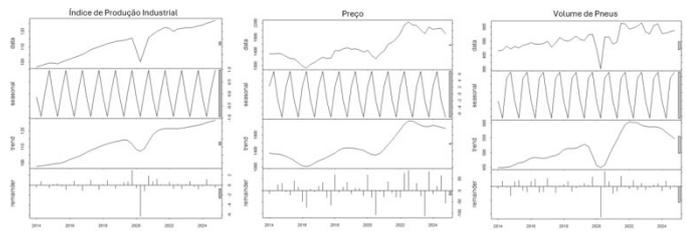
Source: Notch Consulting; prepared by the Author

Figure 6. Additive Decomposition of the Demand Time Series

A similar decomposition was carried out for the explanatory (independent) variables included in the model:

- **Global tire sales volume** – estimated by dividing the global sales volume reported by Goodyear by its market share.
- **Carbon black price** – calculated from Orion Engineered Carbons’ gross revenue divided by volume sold, cross-checked with recent data from publicly available platforms such as Trading Economics.
- **Global industrial production index** – compiled quarterly (base year 2015 = 100) by the United Nations Industrial Development Organization (UNIDO).

The decompositions for these variables are presented in Figure 7.



Source: Authors

Figure 7. Additive Decomposition of Independent Variables

The time series for all three variables display patterns consistent with macroeconomic dynamics, including a structural break in 2020 caused by the pandemic, followed by varying recovery trajectories. Both the industrial production index and tire sales volume exhibited steady growth from 2014 until 2020. After the pandemic shock, tire sales rebounded more quickly but have since stabilized and, in some periods, declined. The industrial production index has resumed its pre-pandemic upward trend.

Carbon black prices have followed a less stable trajectory, with cycles of decline and growth even before 2020. In recent years, prices have stabilized at levels above the pre-pandemic average, possibly reflecting market adjustments and post-crisis inflationary effects. Seasonality is clearly evident in all three series, consistent with regular production and demand cycles. The noise component shows higher volatility during the pandemic period, particularly in tire sales and industrial production. To better understand the relationships between variables, pairwise correlations were calculated, as shown in Figure 8.

industrial production index	1	0,77	0,84	0,82
demand	0,77	1	0,52	0,66
carbon black prices	0,84	0,52	1	0,72
sales volume	0,82	0,66	0,72	1
	industrial production index	demand	carbon black prices	sales volume

Figure 8. Correlation Matrix of Variables

The results reveal a strong positive correlation between the global industrial production index and carbon black prices (0.84), and between the index and tire sales volume (0.82). This suggests that both carbon black prices and tire sales closely track global industrial activity. Demand for carbon black itself is also highly correlated with the industrial production index (0.77) and moderately correlated with tire sales volume (0.66), indicating that overall industrial activity is a more direct driver of demand than tire production alone. This relationship is economically reasonable given that carbon black has multiple industrial applications beyond tire reinforcement. The weaker correlation between demand and price (0.52) suggests a relatively inelastic industrial demand, consistent with the fact that carbon black is often supplied under long-term contracts with key customers, which limits short-term price sensitivity. Overall, the matrix indicates that the global industrial production index is the primary variable associated with carbon black demand, while also highlighting potential collinearity issues among the independent variables.

### System Dynamics Methodology

Participatory System Dynamics (SD) modeling are widely recognized methods for gaining insight into stakeholders' comprehension of the variables, relationships, and feedback loops constituting a complex system (Andersen *et al.*, 2007, Kotir *et al.*, 2024). These approaches enable the collaborative construction of causal maps and simulation models, facilitating the integration of observations, theories, and knowledge from diverse perspectives (Monge *et al.*, 2021; Mattham *et al.*, 2023; Pluchinotta, *et al.*, 2024; Kotir *et al.*, 2024). When evaluating a system using the SD approach, the Causal Loop Diagram (CLD) is first employed for conceptualization modelling (Monge *et al.*, 2022; Kotir *et al.*, 2024). The CLD is a powerful tool to demonstrate the interactions between

variables of a system to obtain a complete visualization to analyse and improve (Gebrai *et al.*, 2021). This intuitive diagram allows a holistic representation of systems, especially critical variables, and feedback loops (cause and effect relationships) (Sterman, 2000; Esfandabadi *et al.*, 2020), reflecting stakeholders' mental models comprised of variables characterized by positive or negative polarity. Positive feedback tends to increase what is happening in the system and shows a state of reinforcement, while negative feedback neutralizes or opposes changes and represents a state of equilibrium (Sterman, 2000; Bala *et al.*, 2017; Kotir *et al.*, 2024).

## Research Design

The development of all CLDs is based on discussions through workshops for interactive activities to engage researchers' participants in the modeling process for its flexibility in fostering a shared understanding of the problem, assumptions, develop models and feedback analysis (Andersen *et al.*, 2007; Kotir *et al.*, 2024; Gaspers *et al.*, 2024). The workshops involve experienced multidisciplinary groups, a total of 10 researchers participated in the collaborative modeling, represented diverse disciplines such as chemical engineer (4), industrial engineer (1), economist (1), marine biology (1), data science (1), electrical engineer (1) and a chemist (1). The decision to involve only researchers is justified by the ease of organizing and participating in group modelling and by the diverse skills and knowledge (experience) that improved the understanding of the problem and offered the opportunity to provide suggestions about the logic and reality of the model. A total of 21 workshops were held in 2023/2024. Throughout all the workshops, discussions were facilitated using a checklist and open-source Vensim® DSS software for Windows for cognitive/concept mapping, allowing for real-time inclusion and exclusion of variables in CLDs.

## Problem and boundary definition

A solid theoretical basis was a prerequisite to ensure the effectiveness of the group modelling discussions through a literature survey (Andersen *et al.*, 2007; Pluchinotta, *et al.*, 2024), a significant number of variables which were further selected to address the problem identification and describe causal relationships. Therefore, the problem definition is based on the following questions: (i) What are the challenges for industrial-scale production from the pyrolysis of waste tires? (ii) How to identify the nonlinear interconnections between the variables of this system?

To answer these questions, the research problem was defined as the need to identify and comprehensively analyze the variables that directly and indirectly influence industrial-scale production from the pyrolysis of waste tires, to understand the non-linear relationship between these variables and to propose evaluation indicators to facilitate the large-scale pyrolysis of waste tires. After outlining the problem, Group Model Building (GMB) agreed upon several assumptions to define the scope of the research and establish boundaries to clarify what the model will encompass and what aspects it will exclude (Matham *et al.*, 2023; Kotir *et al.*, 2024). It is assumed that the feedstock would be supplied by local recycling sources and that pretreatment would involve mechanical shredding methods (with particle sizes ranging from 5 to 20 mm) to feed the standard pyrolysis furnace (Hossain *et al.*, 2023). The

reactor utilized would be a rotary kiln, chosen for its slow heating rate which enables higher heat transfer, and affordable cost (Xu *et al.*, 2021). It is assumed that the reactor units have a production capacity of 4.4 metric tons per hour and an annual operation of 8760 h based on previous researchers and upon industrial designs (Rossain *et al.*, 2023; Rosner *et al.*, 2024; BESTON, 2024). CBp is obtained from the process as well as by-products including tire pyrolysis oil, gas and steel.

## Dynamic hypothesis

Discussions were held to guide the grouping and choice of main subsystems (Figure 9). The key variables and most significant interactions contributing directly to the study's objectives were selected. The GMB understood that the subsystems chosen for analysis have significant relationship with the problem investigated and defined scope. For instance, the national target for the disposal of waste tires increases the waste tire utilization rate for pyrolysis, which positively influences the pyrolysis of waste tires on an industrial scale. The market demand for carbon black increases the need for pyrolysis, which consequently increases the supply of these products. Present technical barriers (such as technological feasibility) have a negative impact on the pyrolysis of waste tires and consequently reduce these technical challenges over time. Moreover, government support and regulations facilitate subsidies and investments for this large-scale production (Lin *et al.*, 2024).

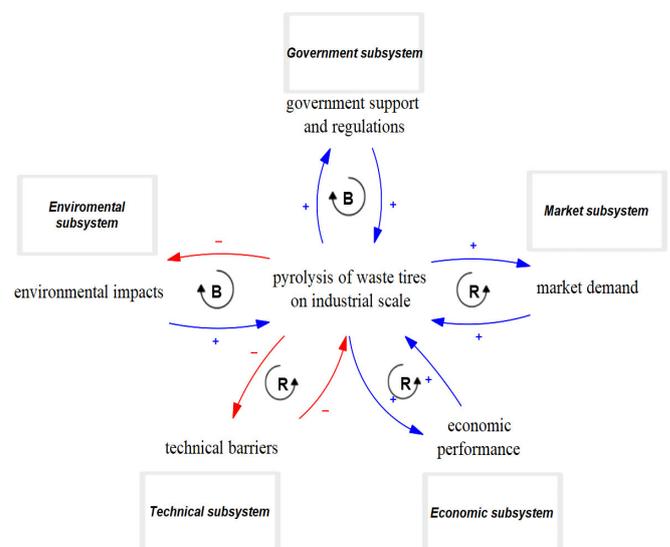


Figure 9. Dynamics assumptions

## Causal Loop Diagrams (CLDs) development

In this stage, the GMB engaged in brainstorming sessions for each dimension separately, where they listed all factors believed to have a direct or indirect impact to be included in the CLDs (George *et al.*, 2015; Pagano *et al.*, 2019; Han *et al.*, 2023; Matham *et al.*, 2023). Given the complexity of the system under investigation, this study simplifies the analysis by focusing on specific subsystems and identifying common variables between them which allows for a more manageable and focused examination, facilitates understanding of the interactions and internal dynamics of each subsystem and concentrates on critical aspects that influence the overall performance of the system, avoiding information overload.

**Validation of feedback identified**

By conducting a literature review and GMB, it was suggested that the most critical feedback mechanisms of waste tire pyrolysis were included. In the first stage, the initial CLD was validated based on the relationships between the identified variables of waste tire pyrolysis that are well documented in the literature (Zabaniotou *et al.*, 2014; Martínez, 2019; Xu *et al.*, 2021; Martínez, 2021; Moasas *et al.*, 2022; Zerín *et al.*, 2023; Zhang *et al.*, 2022; Hossain *et al.*, 2023; Yusha *et al.*, 2024). Besides, all the CLDs developed were discussed and modified during the interdisciplinary workshops. Each member of the GMB participated continuously in the assessment of existing states and relationships and discussions of previous results. After modifications and agreement between the members, the final CLDs, feedback loops and equations were obtained.

**Choosing assessment indicators**

The selected indicators were chosen based on their relevance to capturing and analyzing the essential dynamics of the system under study (Esfandabadi *et al.*, 2020; Coletta *et al.*, 2021). These indicators were identified through a comprehensive analysis of existing literature on tire pyrolysis modeling and reviews, (Xu *et al.*, 2020; Monge *et al.*, 2022; Wu *et al.*, 2024; Yusha *et al.*, 2024; Mouneir *et al.*, 2024, as well as studies on related subjects such as biomass (Jhani *et al.*, 2023; Lin *et al.*, 2024) and plastics (Kunlere *et al.*, 2023) recovery. In the second stage, indicators and common research approaches were identified to enable a quantitative and systematic assessment of the performance of the subsystems. These chosen indicators are grouped under five main dimensions: economic, technical, environmental, market and policy (Table 1).

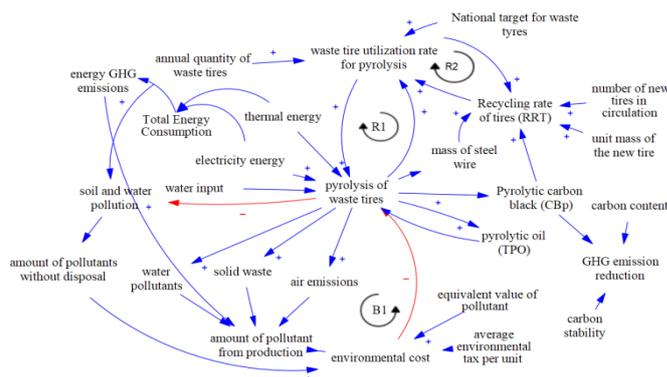
**ANALYSIS**

The results are several models that outline the cause-and-effect relationships between the main variables, incorporating feedback loops considering complex interdependencies between market, environmental, technical and political issues, with the aim of improving the pyrolysis process on an industrial scale and reducing the disposal of waste tires.

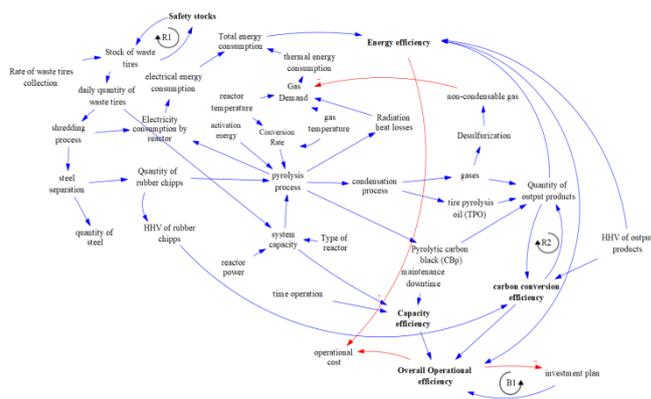
**Environmental subsystem**

Figure 10 captures the main environmental aspects identified for the subsystem under analysis that are driving the dynamics of policymaking to reduce the environmental problems caused by waste tires. Pyrolysis allows for the processing of used tires that might otherwise be disposed of in landfills, contributing to a reduction in the amount of solid waste (Martinez *et al.*, 2021; Wu *et al.*, 2021). As Figure 11 characterizes two reinforcement loops of **R2** and **R3** are shaped to demonstrate the direct impacts on increasing tire pyrolysis from an environmental perspective. The large-scale production of CBp increases the utilization rate of waste tires, and the availability of these wastes positively influences the continued production of carbon black (reinforcing loop-**R1**). In fact, these dynamics explain the need for the availability of waste to be earmarked specifically for the pyrolysis process (Martínez *et al.*, 2013; Xu *et al.*, 2020; Wu *et al.*, 2021; Hossain *et al.*, 2023). The loop (**R2**) shows that an increase in the indicator tire recycling rate (RTT) has a positive influence on the waste tire utilization rate

for pyrolysis, in turn, an increase in the recycling rate leads to targets for pyrolysis efforts.



**Figure 10. CLD for environmental subsystem**



**Figure 11. CLD for technical subsystem**

However, the negative environmental impacts of producing CBp on a large scale must be considered. The process generally requires high temperatures and consumes large amounts of electrical and thermal energy (901.25 kWh/ton) mainly in the pre-processing stage (240 kWh/ton), often derived from fossil fuels (Zabaniotou *et al.*, 2014; Bi *et al.*, 2022; Hossain *et al.*, 2023). This can result in the significant release of amount of pollutant from production that include carbon dioxide (CO<sub>2</sub>), other atmospheric pollutants such as sulphur oxides (SO<sub>x</sub>), nitrogen oxides (NO<sub>x</sub>), particulate matter and volatile organic compounds (VOCs) (Cataldo, 2019; Zhang *et al.*, 2022; Wu *et al.*, 2024). In addition, it can generate by-products and waste, including ash, soot and other unused materials. Improper disposal of this waste can contaminate soil and water, causing negative impacts on local ecosystems and biodiversity (Wu *et al.*, 2021; Rosner *et al.*, 2023). The equilibrium cycle (**B1**) presents an environmental concern. Tire pyrolysis reduces soil and water pollution caused by tire disposal and effectively reduces dependence on coal, as well as replacing natural gas and some of the raw material oil in CB production with pyrolytic oil (Xu *et al.*, 2020; Wu *et al.*, 2021). However, the process generally requires high temperatures and consumes large amounts of electrical and thermal energy (901.25 kWh/ton) mainly in the pre-processing stage (240 kWh/ton), often derived from fossil fuels (Zabaniotou *et al.*, 2014; Bi *et al.*, 2022; Hossain *et al.*, 2023). This can result in the significant release of amount of pollutant from production that include carbon dioxide (CO<sub>2</sub>), other atmospheric pollutants such as sulphur oxides (SO<sub>x</sub>), nitrogen oxides (NO<sub>x</sub>), particulate matter and volatile organic compounds (VOCs) (Cataldo, 2019; Zhang *et al.*, 2022; Wu *et al.*, 2024). Besides, it can generate by-products and waste,

including ash, soot and other unused materials. Improper disposal of this waste can contaminate soil and water, causing negative impacts on local ecosystems and biodiversity (Wu *et al.*, 2021; Zhang *et al.*, 2022; Rosner *et al.*, 2023). Therefore, it was proposed to use indicators to evaluate the environmental cost over time and in different quantities and the tire recycling rate (Eq.1). To minimize environmental costs, it is essential to implement pollution control technologies and optimize energy use (Martinez *et al.*, 2021; Maga *et al.*, 2023; Wu *et al.*, 2024). Eq.1 allows calculate the environmental cost (C), where represents the environmental tax of pollutant,  $E_i$  is the amount of pollutant (kg CO<sub>2</sub> eq/t), and represents the equivalent value of pollutant  $i$  (Wu *et al.*, 2021). The average environmental tax per unit of pollutant can be adopted in accordance with each country's environmental protection tax law. Eq. 2 indicator of the tire recycling rate (RRT) reflects the resource savings obtained by recycling waste tires (WT) to produce tires (Wu *et al.*, 2024). Where represents the mass of steel wire (kg/t-WTs), the mass of CBp, represents the unit mass of the new tire (ton) and represents the number of new tires in circulation (units) (Wu *et al.*, 2024).

$$C = \sum \frac{\mu_i * E_i}{\vartheta_i} \quad (1)$$

$$RRT = \sum \frac{M_{sw} + M_{CBp}}{UM_{NT} * N_{NT}} \times 100\% \quad (2)$$

$$ER_{GHG} = m_{CB}(\text{ton}) * C_{CB}(\%) * C_s(\%) \quad (3)$$

Furthermore, Eq. 3 should be used to calculate the annual reduction in greenhouse gas (GHG) emissions (of pyrolysis plants where, represent the mass of CB(ton), the carbon content of the Cb and the carbon stability, respectively (Hossain *et al.*, 2023; Wu *et al.*, 2024). This indicator can be used to compare the environmental performance of waste tires in pyrolysis with common waste tire recycling methods (incineration, rubber reclaiming,) (Ferdous *et al.*, 2021; Wu *et al.*, 2024). For instance, the impact on GHG from the treatment of 1 t of waste tire (WT) in cement plants is minus 309 kg CO<sub>2</sub>-eq./t WT. The incineration of WT contributes to 1681 kg CO<sub>2</sub>-eq./t WT (Maga *et al.*, 2023). The comparison makes it possible to identify the environmental advantages of the trade-off between pyrolyzing waste tires or common waste tire recycling methods. Additionally, other approaches can be used to analyze environmental performance. For example, life cycle assessment (LCA) quantifies the environmental impacts of the pyrolysis process to understand the total environmental effects in various impact categories (GWP, acidification potential, ozone depletion potential, abiotic depletion potential) (Maga *et al.*, 2023; Wu *et al.*, 2024). Studies based on LCA show that the environmental impacts of CBp production are significantly lower compared to the conventional CB process. The most significant reductions in ozone depletion potential (1298,57%) (Zhang *et al.*, 2022; Wu *et al.*, 2021 and 2024).

### Technical subsystem

The complexity of waste tire pyrolysis technology requires several areas of technical risk (technological development, where there may be uncertainties about its effectiveness and ability to scale up to commercial levels; operational efficiency and stability; safety, which includes the ability to guarantee

worker safety and prevent operational accidents) (Xu *et al.*, 2021; Mouneir *et al.*, 2024). In this study, the focus is on overall operational efficiency, which includes carbon conversion, capacity efficiency, energy efficiency and safety stocks as overall performance indicators to analyze the technical and operational capabilities in the medium and long term.

In Figure 11, the causal relationships within the technical dimension are elucidated. The consistent supply of suitable raw materials proves to be a challenge, with the availability of waste tires subject to seasonal and regional fluctuations (Xu *et al.*, 2021; Rosner *et al.*, 2024). The decision was made to utilize the safety stock concept that resulted in the first reinforcement loop (**R1**). This means that increasing the amount of stock directly influences the safety stock levels (SS) that can guarantee the continuous supply of waste tires. In this study, the design of SS at time  $t$  (Eq.4) is equal to the integral of the stock consumed (C) from  $t_0$  to  $t$  plus the initial stock ( $S_{t_0}$ ), with  $SS_t \leq S_{t_0}$ . The stock consumed (C), also known as consumption, is the derivative of the stock level in relation to time (Ducharme *et al.*, 2021).

$$SS_t = \int_{t_0}^t C dt + S_{t_0} \quad (4)$$

The loop (**R2**) refers to waste tire to pyrolytic output products (pyrolytic oil, char, and syngas) conversion efficiency. The efficiency of carbon conversion increases with the quantity of outputs and the more outputs the greater the efficiency (Hossain *et al.*, 2024). The balancing loop (**B1**) reflects the advantage of analyzing the overall operational efficiency that can decrease investment costs that increase overall efficiency, as it shows how different variables interact to optimize operational performance results and allows for improvements in data-based information for new decisions.

The researchers agreed that Capacity Efficiency (CP) can be calculated by Eq 5. Where QPO is the quantity of product obtained, RC the Reactor Capacity, OT the Operating Time and MD the Maintenance Downtime (Heizer,2021). The carbon conversion efficiency (Eq.6) (Heizer,2021) is calculated as the ratio between the energy contained in the products generated and the energy supplied as input contained in the rubber chips where, HHV denotes the higher calorific value of products and denotes the mass of a particular products output. The energy efficiency (EE) (Eq.7) is the ratio between the energy of pyrolysis products to the total energy consumed (Xu *et al.*, 2021; Hossain *et al.*, 2023; Yusha *et al.*, 2024). These indicators facilitate the assessment of technical and economic potential.

$$CP = \frac{QPO}{RC * (OT - MD)} \quad (5)$$

$$Y_E = \frac{(m * HHV)_{oil} + (m * HHV)_{char} + (m * HHV)_{syngas}}{(m * HHV)_{tire}} \quad (6)$$

$$EE = \frac{\text{energy of pyrolysis products}}{\text{Total energy consumption}} \quad (7)$$

Therefore, Overall Operational efficiency (OPE) can be calculated as the ratio between the values of the indicators mentioned above and the number of comparable and standardized indicators (Eq.8) to obtain an aggregated value that represents the overall performance (Heizer,2021). OPE is

useful as a strategic general indicator to help make decisions about investments in Cb industrial facilities, as it provides a comprehensive view of operational performance, compares performance between different facilities and monitors the effects of improvement initiatives (Tran, 2017).

$$OPE = \sum_t \frac{CP + Y_E + EE}{Quantity\ of\ indicators} \tag{8}$$

**Economic subsystem**

In this subsystem, the dynamic interactions between key economic variables that impact the profitability of tire pyrolysis were identified and analyzed to discuss the main drivers and obstacles that affect investment, production costs and profitability over time. Taking into account that the economic viability of this complex process is fundamental to its large-scale adoption (Bi *et al.*, 2022; Hossain *et al.*, 2023; Rosner *et al.*, 2024). Figure 12 illustrates tree loops: **B1**, **R1**, **R2**, of which **R1** and **R2** are related to initial investment. In fact, initial investment is the main barrier to setting up industrial-scale plants, especially in countries that often lack financial incentives (Zabaniotou *et al.*, 2014).

As demonstrated in Figure 12, the loop **B1** indicates that increases in the scale of production can lead to economies of scale, lowering the levelized cost of carbon black (LCCB). This dynamic occurs because by expanding production, the company can dilute fixed costs, such as infrastructure and technology, over a greater number of units produced, making the project more economical as production increases. The LCCB is an economic indicator that shows the costs of producing carbon black in initial years (Rosner *et al.*, 2024).

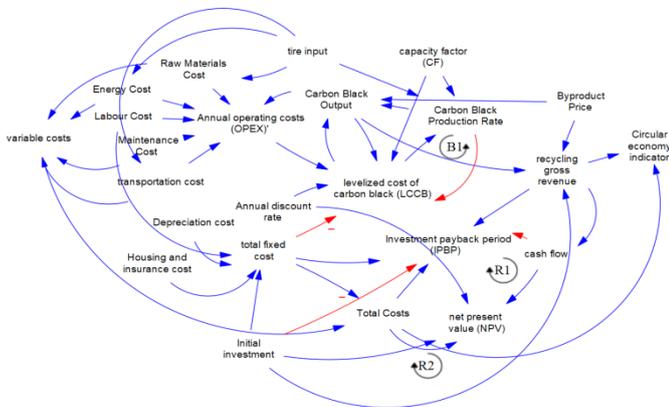


Figure 12. CLD for economic subsystem

In this study, the LCCB is formulated (Eq.9) based on relevant literature, where capital costs (comprise the cost of process equipment, on-site facilities and infrastructure that support the plant, OPEX stands for annual operating costs that includes expenses (rent, utilities, salaries, office supplies), CBP denotes the carbon black output (tons), and *r* is a rate used to calculate the present value of future cash flows (Xu *et al.*, 2021; Hossain *et al.*, 2023).

$$LCCB = \frac{\sum_t \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_t (CB_t^{output})} \tag{9}$$

Loop **R1** states that a positive cash flow over time can reduce the payback time. This creates a positive feedback loop, where

a profitable operation leads to a faster payback, which can further increase the project's financial returns. If a company maintains the expected positive cash flow, considering delays with learning curves leaves possibilities for faster recovery of the initial investment (Hossain *et al.*, 2024). Loop **R2** shows that increased investment can increase revenue, as more resources are available to increase production, leading to an improvement in NPV. A higher NPV can incentivize more investment, creating a positive feedback loop. Additionally, a higher initial investment leads to a lower Payback and NPV but reduces the LCCB over time due to the dilution of the cost in a higher volume of production (Yahya *et al.*, 2021).

Furthermore, a larger initial investment can increase the payback, as more time is needed to recover the initial investment. This can create negative feedback, where a longer payback can reduce the attractiveness of the project. The investment payback period (IPBP) can be calculated using Eq.10 where TFC refers to the total fixed cost at the start of a project, V is the total cost (fixed cost and variable cost) per year of the pyrolysis plant and P is the gross revenue obtained per year (Hossain *et al.*, 2023).

$$IPPB = \frac{TFC}{P-V} \tag{10}$$

In order to effectively measure the circularity of the process, the Circular Economy Indicator (IEC) was formulated (Eq. 11) to assess the positive environmental impact generated by reducing waste and emissions, where represents the recycling gross revenue, and V is the total cost. If IEC=1, the costs are equal to the benefits; and if IEC<1, the operation is not sustainable from a circular economy perspective (Serrano-Arévalo *et al.*, 2024; Dadamo *et al.*, 2024).

$$IEC = \frac{GR_{revenue}}{V} \tag{11}$$

**Political subsystem**

Figure 13 presents the causal relationships between the policy variables identified for the political dimension. The choice of variables was based on the extensive literature available in the area. The analysis by providing insights into how these political elements can influence a country's political risk for the problem under analysis and offer a solid basis for informed strategic decisions in a dynamic global context. Given that political risk refers to the probability that events related to government decisions will negatively impact an investment (Wang *et al.*, 2024; Omri *et al.*, 2024).

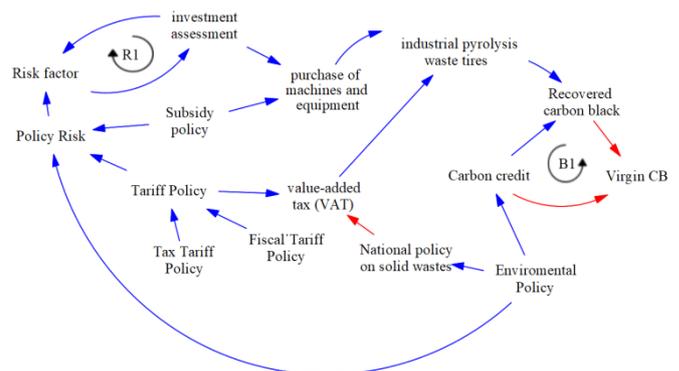


Figure 13. CLD for political subsystem

In general, many authors (e.g., Xu *et al.*, 2020; Martínez, 2021; Araujo-Morera *et al.*, 2021) agree that current policies are not enough to adequately deal with the generation and disposal of waste tires and that joint actions and cooperation with scientists and government institutions are needed. In the short and medium term, it is hoped that policies and regulations will be applied in an integrated manner to achieve a circular economy approach in the countries.

Loop **B1** represents companies that implement industrial pyrolysis waste tires can receive carbon credits based on the amount of carbon emissions they avoid which positively influences the increase in reformed carbon black, replacing part of the virgin carbon black that would normally be produced from fossil fuels, which can lead to a reduction in the demand for virgin carbon black (Zabatinou *et al.*, 2014; Martínez, 2021). Carbon credits are financial instruments that represent the ton of CO<sub>2</sub> avoided, encouraging companies to invest in sustainable technologies and helping to mitigate climate change (Feitosa *et al.*, 2023).

Loop **R1** shows that if political risk increases, investors may consider tire pyrolysis projects to be riskier investments. This can increase the cost of capital and further increase the investment risk. Therefore, an increase in political risk leads to an increase in investment risk, which in turn can further increase political risk, and thus be detrimental to the attractiveness and viability of investing in the projects. Investors demand higher returns to compensate for the additional risks (Zabatinou *et al.*, 2014; Jahani *et al.*, 2023; Wang *et al.*, 2024). This scenario creates a feedback loop: as the viability of projects decreases, the environment of political uncertainty intensifies, generating even greater disinterest in sectors that could boost sustainability.

Besides, the integration of policies regarding tariff policy, environmental policy and political subsidy was formulated in the equation (12) based on (Jahani *et al.*, 2023; Sun *et al.*, 2024). The includes the political variables chosen based on their ease of quantification considering their respective impact coefficients (%).  $P_i$  represents probabilities (between 0 and 1) and  $K$  are coefficients or weights that have the same dimensions as the impact associated with them. For example, if the impact is in money, the weights will also be in monetary units.

$$Risk_p = P_i^{tax} * K_{tax} + P_i^{sub} * K_{sub} + P_i^{env} * K_{env} \quad (12)$$

$$\frac{dl}{dt} = -k \cdot Risk_p(t) \quad (13)$$

Therefore, it was possible to formulate the equation that captures how political variables affects the investment decision. Where  $I(t)$  is the level of investment in a given period of time  $t$ , at a given time  $t$ ,  $k$  is a factor (%) that indicates the sensitivity of investment to political risk. Thus, the higher the value of the greater the risk perceived by investors. If increases (indicating an increase in political risk), then becomes negative, which means that investment  $I(t)$  is decreasing over time.

**Market subsystem**

The market subsystem (Figure 14) include market access barriers, marketing capacity, market price and demand

uncertainty. It is important to mention that the products resulting from the pyrolysis of waste tires are marketed in solid and stable markets, meaning that replacing Virgin CB with Recovered CB requires strategies to improve the reputation of pyrolysis products (Xu *et al.*, 2021; Zerin *et al.*, 2023). The Market Groth Potential (MGP) factor is the overall attractiveness of the carbon black market. The researchers agreed that it can be modeled as a function (Eq.14) of the size of the market and the demand for pyrolysis products. Then, a positive loop is identified (R1), which MGP can increase the demand for carbon black, at the same time, will lead to more efforts for MGP (due to effective sustainable decisions), which directly influences carbon black production.

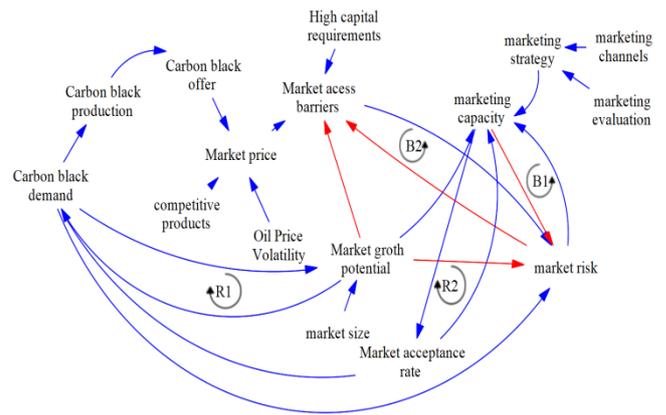


Figure 14. CLD for market subsystem

$$MGP = f(CB_D, MKT_{SZ})t \quad (14)$$

$$MKT_{cp} = f(MKT_{ST}, MKT_{AR})t \quad (15)$$

In addition, greater MGP can attract more investment and reduce perceptions of risk. This can reduce market access barriers, allowing for greater penetration by new players (Martínez, 2021; Dong, *et al.*, 2024). Products derived from the pyrolysis of waste tires can be of unexpected quality. For example, the pyrolizer does not have the technological tools to ensure proper operating conditions (Martinez, 2021). Hence, it's important to analyze the marketing capacity because otherwise there is no market penetration. The is modeled as the function of the marketing strategies (adopted and the public acceptance (of pyrolysis-derived products. Better marketing strategies can reduce the perception of market risk and therefore allow for a more effective allocation of resources to marketing strategies (Loop B1). can increase the rate of market acceptance, which increases the effectiveness of marketing strategies and can increase demand for Cb (Martínez, 2021).

The market access barrier (MAB) is described as the function of MGP and capital requirements (CR) (Eq. 14). Furthermore, it was agreed among the researchers that the negative loop (B2) is justified because MAB increases market risk, causing additional costs and operational difficulties and the waste tire pyrolysis market can present a high perceived risk and investment that can discourage new investments and limit market access. In addition, high price volatility can increase access barriers due to economic and financial uncertainty (Dong, *et al.*, 2024).

$$MAB = f(MGP, CR)t \quad (16)$$

Therefore, in this research market risk is defined as a weighted combination of the factors discussed above and their respective impact coefficients (W) to facilitate market penetration (Eq. 15).

$$MKT_{risk} = (W1. MGP + W2. MKT_{cp} + W3. MAB)t \quad (17)$$

## DISCUSSION

The results discussed provided several political, economic, environmental, market and technological recommendations to address the issues raised in developed model's framework.

### Environmental implications

Mapping the relationships within the causal loop diagram (CLD) provides a system-wide view of how various measures and practices interact to influence the environmental sustainability of carbon black production. By making feedback structures and interdependencies explicit, the CLD helps identify high-leverage intervention points where small changes can yield significant environmental benefits. Targeted strategies may include adopting energy-efficient and environmentally friendly technologies - such as advanced filters and scrubbers for emission control - while simultaneously establishing a sustainable and traceable waste tire supply chain to alleviate pressure on natural resources and support biodiversity conservation. Within the model's framework, these interventions reinforce virtuous feedback loops that align with environmental regulations, industry best practices, and long-term low-carbon objectives. Together, they form a coherent pathway for reducing the environmental footprint of CBp production while supporting a systemic transition toward sustainability.

### Technical implication

The analysis of the causal loop diagrams (CLDs) and associated models for pyrolysis technology reveals specific leverage points for technological improvement and innovation. By embedding technical parameters and performance indicators within the system dynamics framework, the models enable a more comprehensive assessment of process efficiency, operational reliability, and scalability. This systems-based perspective facilitates the identification of intervention points where targeted technological enhancements - such as process heat recovery, advanced emission control systems, and optimized feedstock preparation - can significantly improve overall performance. From a policy and market perspective, the integration of technical insights with environmental, economic, and regulatory subsystems underscores the need for coherent strategies that align technological development with broader sustainability goals. Reliable, medium- to long-term pyrolysis operations require not only robust engineering solutions but also supportive regulatory frameworks, stable supply chains, and market mechanisms that incentivize renewable energy production from waste tires. By bridging technical performance with systemic considerations, the research offers actionable guidance for engineers, policymakers, and industry leaders aiming to develop pyrolysis facilities that are both technologically sound and economically viable within a circular economy framework.

### Economic implications

The modeling framework developed in this study offers a powerful tool for evaluating the economic viability of waste tire pyrolysis projects. By embedding financial indicators within the causal loop diagrams (CLDs), the analysis captures how economic performance is shaped by dynamic interactions between market conditions, technological efficiency, regulatory factors, and supply chain stability. Understanding these feedback structures is critical, as changes in one variable - such as feedstock availability, energy prices, or carbon credit valuation - can propagate through the system, altering cost structures, revenue streams, and overall project profitability over time. Positioned within the broader framework of the circular economy - which aims to maximize material value, minimize waste, and reduce dependence on virgin raw materials (Martínez *et al.*, 2014; Xu *et al.*, 2020; Araujo-Morera *et al.*, 2021; Kunlere *et al.*, 2023) - pyrolysis emerges as a commercially relevant and technically feasible pathway. By transforming end-of-life tires into marketable outputs such as pyrolytic carbon black and recovered oils, the process supports a closed-loop production system that conserves resources and mitigates environmental impacts (Antoniou *et al.*, 2019). From an economic perspective, these outputs can generate diversified revenue streams while displacing higher-cost virgin materials, improving competitiveness in both carbon black and energy markets. Additionally, by contributing to waste diversion and emissions reduction, pyrolysis can position project developers to benefit from environmental incentives and emerging low-carbon market mechanisms. Beyond its direct financial returns, the technology drives broader economic value by stimulating innovation, advancing environmental technology adoption, and creating new opportunities for industrial symbiosis (Magagula *et al.*, 2023; Mouneir *et al.*, 2024).

### Political implications

The modeling results provide a structured lens for understanding how policy decisions influence the adoption, scaling, and long-term viability of waste tire pyrolysis. By mapping the interactions between regulatory frameworks, technological deployment, market incentives, and environmental objectives, the models help anticipate how shifts in legislation, subsidies, or environmental standards could impact the sector's development trajectory. This systemic perspective is particularly valuable for policymakers seeking to design coherent strategies that align waste management, climate action, and circular economy goals. Moreover, the participatory modeling process fosters dialogue between stakeholder's government agencies, industry representatives, researchers, and civil society supporting the formulation of policies that are both technically feasible and socially acceptable. Insights generated from the model can guide the creation of targeted regulatory instruments, fiscal incentives, and compliance frameworks that accelerate pyrolysis adoption while ensuring environmental safeguards. In this way, the research contributes directly to policy design that advances the transition toward a more circular and sustainable economy.

### Market implications

The analysis of market-related causal loops within the modeling framework enables a systemic understanding of the

business environment surrounding waste tire pyrolysis. By examining the interplay between demand for pyrolytic products, price volatility, supply chain reliability, and competitive positioning, the models help forecast market trends and anticipate structural changes in the sector. This dynamic perspective supports early identification of both risks such as raw material shortages or market saturation and opportunities, including the emergence of new value chains or premium markets for sustainable products. For companies, investors, and policymakers, these insights provide a foundation for evidence-based strategic planning. They facilitate investment decisions, market entry strategies, and risk mitigation approaches tailored to evolving market conditions. Furthermore, the ability to simulate different market scenarios within the model offers a valuable decision-support tool for aligning business strategies with long-term sector growth, technological innovation, and sustainability objectives.

## Conclusion

Advancing sustainable resource management requires the development of more sophisticated dynamic models to deepen understanding and improve predictive capacity. Such models can bridge academic research and practical application, informing strategies and policies that promote environmental sustainability and foster innovation in waste management. This study demonstrates the potential of participatory system dynamics modeling to address complex challenges, focusing on large-scale waste tire management and carbon black production. By engaging stakeholders across disciplines, the research enables robust co-production of knowledge on interconnected economic, political, technical, and environmental subsystems, revealing their interdependencies and feedback loops. The resulting causal insights provide powerful decision-support tools for policymakers and industry leaders, supporting evidence-based assessments of interventions and policies in the tire waste pyrolysis sector.

The findings contribute to academic discourse by outlining concrete pathways to enhance the viability and sustainability of waste tire pyrolysis. They offer practical guidance for strategies that advance environmental objectives, stimulate innovation, and increase efficiency in complex industrial processes. Beyond process-specific insights, the study proposes a transferable framework for analyzing and solving multi-dimensional challenges across technical, political, market, and environmental domains. The results also inform feasibility analyses for substituting recovered CB from waste tires for virgin CB, reinforcing pyrolysis as a viable circular economy strategy. The research, however, has limitations. The models represent a simplified abstraction of the complex dynamics of waste tire management and carbon black production, constrained by the availability and quality of data. These limitations may affect the accuracy and robustness of results, despite the application of group modeling techniques. Furthermore, practical implementation may face barriers - such as legal or social constraints - that were beyond the study's scope. Future work should prioritize more detailed dynamic modeling and scenario-based simulations to refine predictive accuracy and address current limitations. Such developments will strengthen the capacity of system dynamics to guide sustainable, economically viable, and policy-relevant waste tire pyrolysis initiatives.

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